

The nature of the $\Lambda(1405)$

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Abstract. We present here some results supporting the nature of the $\Lambda(1405)$ resonance as dynamically generated from the meson baryon interaction in coupled channels and resulting from the superposition of two close-by poles. We find support for this picture in the $K^-p \rightarrow \pi^0\pi^0\Sigma^0$ reaction, which shows a different shape than the one obtained from the $\pi^-p \rightarrow K^0\pi\Sigma$ reaction. We also call the attention to the $K^-p \rightarrow \gamma\pi\Sigma$ with $\pi\Sigma$ in the $\Lambda(1405)$ region, which shows a narrow peak in the calculations around 1420 MeV. We also report on recent calculations of the radiative decay of the two $\Lambda(1405)$ states and on reactions to obtain information on these decay modes. Finally, we present results for the $pp \rightarrow pK^+\Lambda(1405)$ reaction recently measured at ANKE/COSY and compare them with theoretical results.

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1 Introduction

The $\Lambda(1405)$ resonance has a long history as a dynamically generated resonance from the interaction of meson baryon coupled channels [1,2] but its study has become more systematic with the advent of chiral unitary theories [3,4,5,6,7,8,9,10,11,12]. One of the interesting surprises was that in [8] it was found that the empirical $\Lambda(1405)$ corresponded in fact to two poles (see fig. 1).

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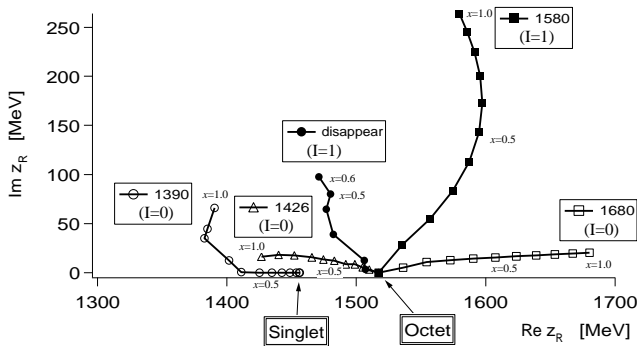


Fig. 1. Trajectories of the poles in the scattering amplitudes obtained by changing the SU(3) breaking parameter x gradually from zero to one. At the SU(3) symmetric limit ($x = 0$), only two poles appear, one is for the singlet and the other for the octet. The symbols correspond to the step size $\delta x = 0.1$.

In the figure one can see trajectories which are obtained when SU(3) symmetry is broken gradually. Recall that we have the interaction of the octet of pseudoscalar mesons and the octet of stable baryons. Hence

$$8 \otimes 8 = 1 \oplus 8_s \oplus 8_a \oplus 10 \oplus \overline{10} \oplus 27, \quad (1)$$

and we get two octets and a singlet where the interaction is attractive. When all the masses of mesons are made equal and the baryon masses equal (SU(3) symmetric case) there is a degeneracy of the two octets. When the masses gradually move to the physical ones the poles follow the trajectories in the figure and then we see that in the region of the $\Lambda(1405)$ there are two poles one coming from an octet and the other one from the singlet. The one around 1420 MeV is narrow and couples mostly to $\bar{K}N$ while the one around 1395 MeV is wide and couples mostly to $\pi\Sigma$. Recently there have been many works implementing effects of higher order Lagrangians in $\bar{K}N$ and coupled channels [13,14,15,16]. They all share these basic features but there are variations as to the width of the lighter state, which is very wide in all approaches. The study of theoretical uncertainties in [16] shows that the lowest order results of [5] fall within theoretical uncertainties.

2 The $K^-p \rightarrow \gamma\pi\Sigma$ in the $\Lambda(1405)$ region

With the discussion above one expects that different reactions produce different shapes for the $\Lambda(1405)$, depending on which of the two states is more strongly excited. In this sense, let us take the process $K^-p \rightarrow \gamma\pi\Sigma$ with the $\pi\Sigma$ in

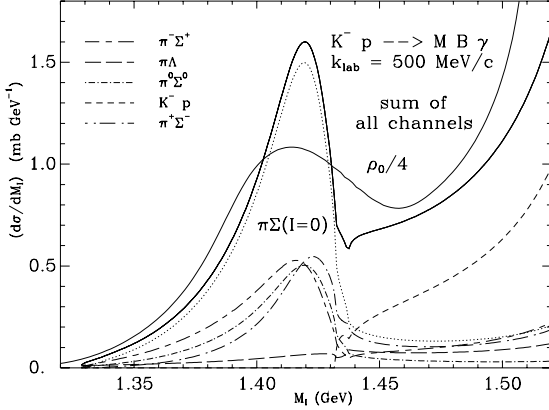


Fig. 2. Mass distribution for the different channels, $\pi^+\Sigma^-$, $\pi^-\Sigma^+$, $\pi^0\Sigma^0$, $\pi\Lambda$, K^-p . The solid line with the resonance shape is the sum of cross sections for all channels. Dotted line: pure $I=0$ contribution from the $\Sigma\pi$ channels. The effects of the Fermi motion with ($\rho = \rho_0/4$) is shown with solid line. The labels for the other lines are shown in the figure.

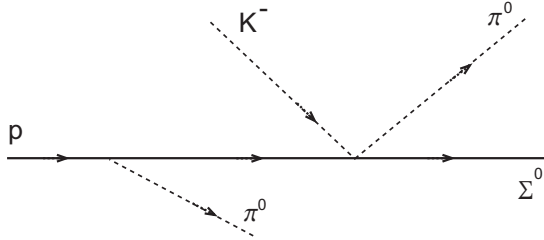


Fig. 3. Dominant mechanisms for the $K^-p \rightarrow \pi^0\pi^0\Sigma^0$ reaction

the $\Lambda(1405)$ region. This reaction was studied in [17] and was found to be dominated by initial state radiation from the K^- . Hence, the $\Lambda(1405)$ is formed from K^-p with a K^- that has lost energy and we should expect it to be dominated by the high energy pole that couples strongly to $\bar{K}N$. This is indeed the case as can be seen in fig. 2. The peak of the cross section appears around 1420 MeV and the width is about 30 MeV, narrower than the nominal one of around 50 MeV. This is one of the experiments that we encourage to be performed and which will provide useful information on the nature of the $\Lambda(1405)$ and its two pole structure.

3 The $K^-p \rightarrow \pi^0\pi^0\Sigma^0$ reaction

This reaction was studied experimentally in [18] and theoretically in [19]. The reaction is similar to the former one but the process is dominated by one π^0 emission from the initial proton, as can be seen in fig. 3.

Once the K^-p system loses energy after the π^0 emission, we can have the right energy to produce the $\Lambda(1405)$ which decays into $\pi^0\Sigma^0$. The interesting thing is that the $\Lambda(1405)$ is once again excited by $\bar{K}N$ and this will give weight to the higher mass pole, resulting in a peak at

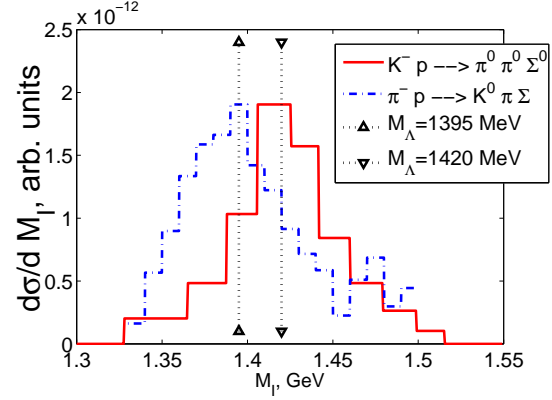


Fig. 4. Two experimental shapes of $\Lambda(1405)$ resonance

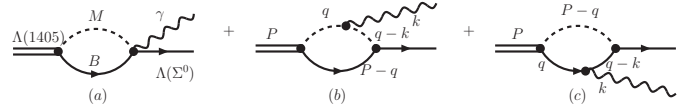


Fig. 5. The radiative decay mechanism of the $\Lambda(1405)$, where MB can be any of the four charged channels of the ten coupled channels: K^-p , \bar{K}^0n , $\pi^0\Lambda$, $\pi^0\Sigma^0$, $\eta\Lambda$, $\eta\Sigma^0$, $\pi^+\Sigma^-$, $\pi^-\Sigma^+$, $K^+\Xi^-$, and $K^0\Xi^0$.

higher masses and narrower than in other experiments which are dominated by the lighter mass pole. This is exactly what happens as one can see in fig. 4, where the shape of the $\Lambda(1405)$ for the $K^-p \rightarrow \pi^0\pi^0\Sigma^0$ reaction are superposed with that of the $\pi^-p \rightarrow K^0\pi\Sigma$, which according to [20] is dominated by the smaller mass pole.

4 Radiative decay of the $\Lambda(1405)$

Radiative decay of the $\Lambda(1405)$ can be another tool to learn about the nature of this resonance. A recent study from the present perspective has been done in [21]. The idea is that since the resonance is like a molecule of meson baryon in different channels, the photon must be radiated from the meson or baryon components. Then the determination of the radiative width is done by evaluating the diagrams of fig. 5.

The results obtained are shown in table 1, where they are compared with other models.

As one can see in the table, the values we obtain for the radiative decay into $\gamma\Lambda$ and $\gamma\Sigma$ depend on which one is the state that decays. This is novel to other approaches where there is only one $\Lambda(1405)$. Obviously in different experiments one will get a different combination of the contribution of the two poles. For this reason in [21] two reactions were studied which give different weight to either of the poles, resulting in different shapes for the $\Lambda(1405)$ resonance and different strength for the radiative width. We studied the reactions $K^-p \rightarrow \pi^0\gamma\Lambda(\Sigma^0)$ and $\pi^-p \rightarrow K^0\gamma\Lambda(\Sigma^0)$. We found different strength and shapes for the two cases and the Λ or Σ in the final state. The results can be seen in figs. 6 and 7.

Table 1. The radiative decay widths of the $\Lambda(1405)$ predicted by different theoretical models, in units of keV. The values denoted by “U χ PT” are the results obtained in the present study. The widths calculated for the low-energy pole and high-energy pole are separated by a comma.

Decay channel	U χ PT	χ QM [23]	BonnCQM [24]	NRQM	RCQM [27]
$\gamma\Lambda$	16.1, 64.8	168	912	143 [25], 200, 154 [26]	118
$\gamma\Sigma^0$	73.5, 33.5	103	233	91 [25], 72, 72 [26]	46
Decay channel	MIT bag [26]	chiral bag [28]	soliton [29]	algebraic model [30]	isobar fit [31]
$\gamma\Lambda$	60, 17	75	44,40	116.9	27 ± 8
$\gamma\Sigma^0$	18, 2.7	1.9	13,17	155.7	10 ± 4 or 23 ± 7

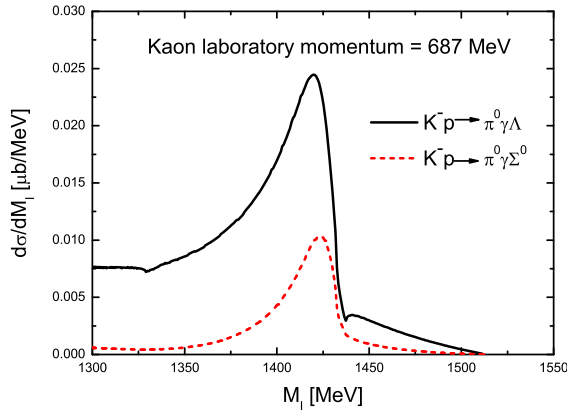


Fig. 6. The invariant mass distribution of $K^- p \rightarrow \pi^0 \gamma \Lambda(\gamma \Sigma^0)$ as a function of the invariant mass of the final $\gamma \Lambda(\gamma \Sigma^0)$ system.

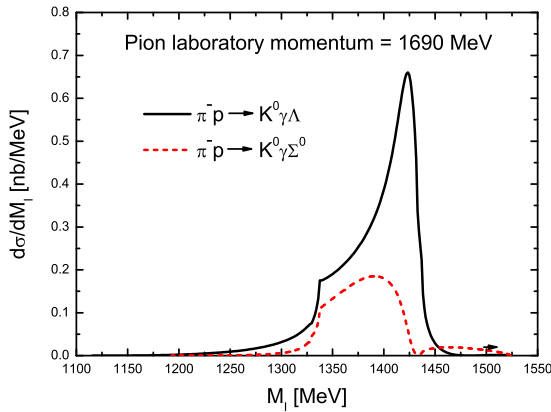


Fig. 7. The invariant mass distribution of $\pi^- p \rightarrow K^0 \gamma \Lambda(\gamma \Sigma^0)$ as a function of the invariant mass of the final $\gamma \Lambda(\gamma \Sigma^0)$ system.

The experimental determination of the strength and shape of these reactions is again one good test for the two pole structure of the $\Lambda(1405)$ and its nature as a dynamically generated resonance.

5 The $pp \rightarrow pK^+ \Lambda(1405)$ reaction

A recent experiment performed by the ANKE collaboration at COSY [32] has also observed the $\Lambda(1405)$ in the $pp \rightarrow pK^+ \Lambda(1405)$ reaction. It is a challenge to reproduce this reaction and in a recent work we have undertaken the task of evaluating the invariant mass distribution.

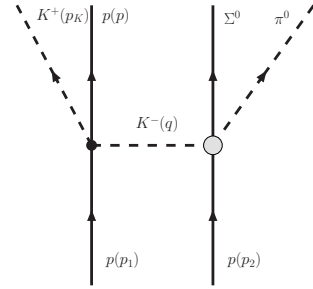


Fig. 8. The kaon exchange mechanism of the $pp \rightarrow pK^+ \Lambda(1405)$ reaction.

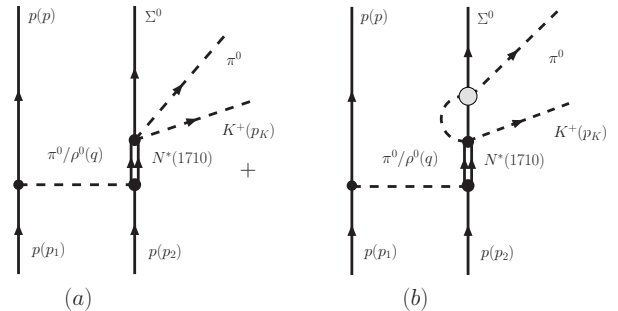


Fig. 9. The pion (rho) exchange mechanism of the $pp \rightarrow pK^+ \Lambda(1405)$ reaction through N^* excitation.

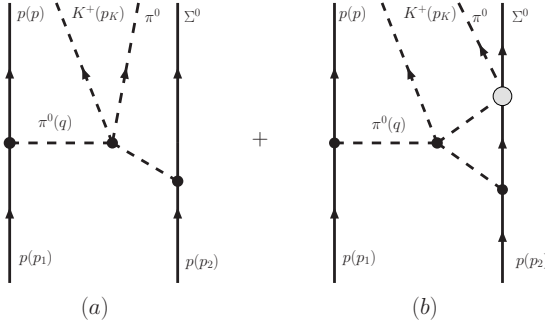


Fig. 10. The pion exchange mechanism of the $pp \rightarrow pK^+\Lambda(1405)$ reaction through meson cloud.

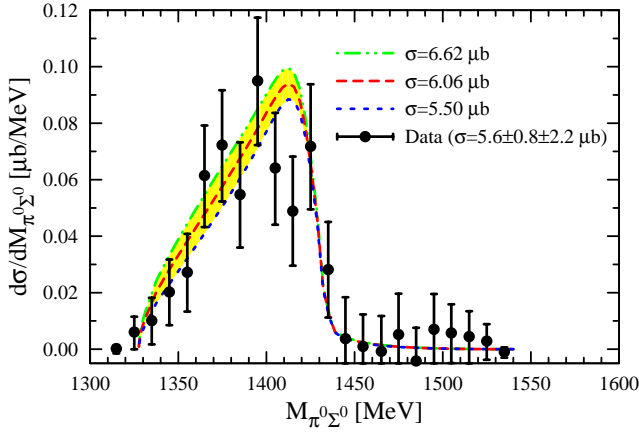


Fig. 11. The invariant mass distribution of the $\pi^0 \Sigma^0$ with theoretical uncertainties estimated using Monte-Carlo sampling method (see [33] for details), in comparison with the data [32]. The theoretical cross section for $\pi^0 \Sigma^0$ production is multiplied by a factor of three to compare with the experimental numbers which have also been multiplied by this factor.

The study conducted in [33] has shown that the mechanism is dominated by Kaon exchange in s-wave (see fig. 8), but the pion exchange (see fig. 9) helps bring some strength at lower invariant masses. The exchange of a ρ meson has also been taken into account. Its contribution is small and contributes mostly to the uncertainties. The pion exchange can also contribute via the diagram of fig. 10, which involves the pion-pion interaction. In fig. 11 we see that the shape of the cross section is well reproduced. We provide numbers in the figure but the comparison is made with data which are given in arbitrary units. The integrated cross section is obtained also fairly, but at the expense of putting some form factors in the virtual K exchange in s-wave, of natural size, but for which no other experimental information is available. The shape is rather independent on the form factor. The strength of the experiment, which has also large uncertainties, could be used to set some boundaries on the size of these form factors.

6 Conclusions

We have reported on several reactions which can provide information on the nature of the $\Lambda(1405)$ and its two pole structure, which is obtained now in all the works using the chiral unitary approach. We have seen that in different reactions one always has an overlap of the two resonant states in such a way that two peaks are not seen in any reaction. Yet, the shape changes from one to another reaction depending on the weight by which each of the states is populated. We showed some reactions that show indeed different shapes, and we could provide an explanation based precisely on the existence of the two poles. Then we suggested several other reactions, feasible in present experimental facilities, which should provide extra relevant information on the existence of these two poles and the nature of the resonance. The predictions made in the present work should serve to encourage the performance of these experiments in the near future.

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